THE ROLE (RELATIONSHIP) OF VISUAL AND MOTOR IMAGERY IN ESTIMATING REACH

A Dissertation

by

DIALA FOUAD AMMAR

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2006

Major Subject: Kinesiology

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Approved by:

Chair of Committee, Carl Gabbard
Committee Members, David Wright
John Buchanan
Teresa Wilcox
Head of Department Steve Dorman

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ABSTRACT

The Role (Relationship) of Visual and Motor Imagery in Estimating Reach.

(May 2006)

Diala Fouad Ammar, B.S., American University of Beirut;

M.A., Sam Houston State University

Chair of Advisory Committee: Dr. Carl Gabbard

The primary intent of this study was to explore fundamental questions about the role and relationship between motor (MI) and visual (VI) imagery within the context of estimating reach. Experiment 1 examined and compared VI and MI tasks under matched environmental conditions with the intent to explore the distinction and cooperation of the visual and motor systems in representing actions. The design of this experiment included an interference paradigm modified from Stevens (2005) in which six blocks of trials (conditions) were used: MI, VI, MI with visual interference, MI with motor interference, VI with motor interference, and VI with visual interference. Results indicated that MI was significantly more accurate than VI in regard to total error, distribution of error and mean bias ($p \leq .05$). Significant increases in the number of errors and estimation bias were found when the modalities for the imagined task and the interference task were matched. The data showed that motor tasks interfered with the ability to MI**,** whereas visual tasks interfered with the ability to VI. Experiment 2 included a response-delay paradigm modified from Bradshaw and Watt (2002) in which eight blocks of trials were used: MI and VI conditions with no-delay and delays of 1-, 2- and 4 s. Overall, this experiment demonstrated that response-delay influenced accuracy of the MI

(visuomotor) task, but not the VI (perceptual) task. That is, after a 4s delay, error in MI increased significantly. Interestingly, these results may indicate a crucial temporal constraint for the representation of distance, isolated in the visuomotor system. In view of both experiments, the findings are consistent with the notion of a distinction between vision for perception (VI) and vision for action (MI) as advanced by Goodale, Westwood & Milner (2004). In conclusion, VI seems to delineate relevant spatial parameters within the environment and then transfer the information to MI. At this point, information is computed in terms of biomechanical possibilities for a certain movement. In summary, just as perception and action are firmly linked, so too are MI and VI.

DEDICATION

To my father Fouad and my mother Sara,
for their unconditional love and support.

ACKNOWLEDGMENTS

I would like to express my sincere appreciation to Dr. Carl Gabbard for serving as chair of my committee during my four years at Texas A&M. Dr. Gabbard provided countless hours of individual attention, sharing his knowledge, experience, and friendship throughout this journey. I would also like to thank the members of my committee: Dr. David Wright, Dr. John Buchanan and Dr. Teresa Wilcox for all their help and encouragement in every stage of this project.

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Finally, I have no way to really thank my family, Fouad, Sara, Youssef, Tamara and Bassel for their endless love and support; without them I would have never made it this far.

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CHAPTER I

INTRODUCTION

Understanding the perception to action dynamics involved in reaching and grasping an object constitutes one of the most mystifying issues in motor behavior research. These actions require a complex set of perceptual to motor transformations. One of the initial steps is to derive a perceptual estimation of the object's distance and location relative to the body. Complementing this process, the individual must scale the distance of the object in terms of his or her effective reach capabilities, which are constrained by both physical and mechanical factors. From a Gibsonian view (1979), the detection of the affordance for a particular mode of reaching entails perceiving whether the reach action will fit in the existing layout of the environment. This means that an individual must be able to perceive critical reach distances beyond which a particular reach action is no longer afforded and to which a transition to another reach mode must occur. Is the object close enough to reach while seated, or does one need to stand up to contact the object? *Arguably, this estimation forms the initial cognitive basis of the motor program, i.e., the cognitive level of action processing*. The long-term goal of this research is to understand the mechanisms underlying this segment of action processing and its relation to motor execution.

This dissertation follows the style of *Research Quarterly for Exercise and Sport.*

The study of imagined versus actual movement affords an attractive approach in the quest to identify the specific mechanisms and relationships involved in action processing. One form of imagined movement, which is the focus of the work reported here, is perceived reach – the comparison between actual and perceived reach outcomes. Since Jeannerod (1994) made one of the initial arguments that action planning and motor preparation can be studied effectively using motor imagery, a multitude of studies have followed. Broadly speaking, imagined movement, also known as motor and kinesthetic imagery, is an active cognitive process during which the representation of a specific action is internally reproduced in working memory without any overt motor output (Decety & Grezes, 1999). Motor imagery has also been described as the class of images of one's own bodily movements that are used to simulate or 'plan for subsequent action'. An important point with relevance to the present work is the distinction between motor imagery (MI) and visual imagery (VI). For successful movement, perceptual information needs to be transformed into action and the actor needs to consider biomechanical constraints, the spatial environment and the relationship between the two (Stevens, 2005). MI represents the kinesthetic and biomechanical constraints connected with the action, while VI is associated with the spatial component of the perceived environment. Nevertheless, the relationship between VI and perception is much less complex than the relationship between MI and action. In MI, estimation of reach takes into account biomechanical constraints, which are not considered in the case of VI. However, MI is often associated with actions displayed within a visual environment; therefore leading many to suggest that MI and VI cannot be entirely separated.

Motor and Visual Imagery

In regard to the general topic of imagined versus actual movement, a review of contemporary work, including neuroimaging studies, suggests quite convincingly that both share common (overlapping) neurocognitive networks which result in a high correlation between real and imagined movement (Decety, 1996; Glover, Dixon, Castiello,&Rushworth, 2005; Gonzalez, Rodriguez. Ramirez, & Sabate, 2005; Michelon, Vettel, & Zachs, 2006; Sheng, Latash, & Zatsiorsky, 2004) (also see Grezes & Decety's [2001]) meta-analysis). Real and imagined movements activate many of the same brain regions, namely the primary and supplementary motor areas, pre-motor cortex, and the cerebellum (Gerardin, Sirigu, Lehericy, Poline, Gaymard, Marsault, et al., 2000; Jeannerod, 2001, Takahashi, Hayashi, Ni, Yahagi, Favilla, & Kasai, 2005). However, it has also been suggested that, although the same network is involved in both real and imagined movements, the functional connectivity (coupling characteristics) within the network differs (Kilner, Vargas, Duval, Blakemore, & Sirigu, 2004; Solodkin, Hlustik., Chen, & Small, 2004). This general notion follows the reasoning of others that although imagined and actual movements may run in parallel (overlapping) networks, there appears to be dissociation at some level (Fischer, 2005; Johnson, Corballis, & Gazzaniga, 2001; Schwoebel, Boronat, & Coslett, 2002).

Behaviorally, a consistent body of research shows that the duration of imagined movements ‘mirror’ executed actions (Decety, 1996; Gentilluci, Roy, & Stefanini, 2004; Papaxanthis, Pozzo, Skoura, & Schiepati, 2002; Sabaté, Gonzales, & Rodriguez, 2004). Complementing the ‘mirror’ observation, several studies also reveal that imagined

movements support Fitt's Law – showing that, imagined movement duration like actual movement duration, increases with increasing task difficutly (Maruff, Wilson, De Fazio, Cerritelli, Hedt, & Currie, 1999; Sabaté, et al., 2004; Stevens, 2005). In regard to hemispheric control and limb use, it has also been reported that imagined movements, like real actions, are controlled primarily by the hemispheres contralateral to the imagined limb (Maruff et al., 1999). In addition, the researchers went on to suggest that imagined movements are subject to the same environmental and physiological constraints as real motor performance. Complementing these observations are reports that the left-hemisphere (in right-handers) may have an advantage over the right brain in regard to imagined movement accuracy. This general finding has been shown in behavioral studies (Johnson, 2000; Maruff, et al., 1999; Sabate et al., 2004) and via examination of functional hemispheric asymmetry using motor evoked potentials (Yahagi & Kasai, 1999).

As stated earlier, VI requires the representation of the spatial components of the perceived environment. A sizable body of literature suggests that VI retains spatial properties of scenes or objects. For example, Dennis and Cocude (1989) asked participants to scan a memorized map and an actual map. It took the same amount of time to complete either task. Explanations for VI have been supported by several behavioral and clinical experiments. For example, Behrmann, Winocur, and Moscovitch, (1992) reported that agnostic patients who lost the ability to recognize visual objects, retained the capacity to visualize images. Observations from brain-damaged patients show that preserved and impaired characteristics of visual perception

are similarly preserved or impaired during a VI task. The idea of overlapping networks between perception and imagery was also reported in a set of experiments looking at normal subjects. For example, Goldenberg, Podreka, Steiner, Willmes, & Deecke, (1989a, 1989b) used a regional cerebral blood flow analysis and reported activation of occipital and inferior temporal regions in normal participants performing VI and perception tasks. Similar findings have been reported after monitoring brain electrical activity (for a review, see Farah, Hammond, Levine, & Calvanio, 1988). The experiments mentioned above suggest that mental images in the visual modality are supported by the same neural substrate as perceptual images generated during normal perception. According to Jeannerod (1994), the precise relationship remains unclear. As Musseler, Steininger and Wuhr (2001) so eloquently concluded - *where perceptual processes end, cognitive processes start, and execution of motor actions begin, is key and yet to be defined*.

Most imagery studies have focused on VI to represent perception or on MI to signify action - the relationship between the two has received little attention (e.g., Stevens, 2005). Roland and Friberg (1985) studied an integrated visual-motor imagery task involving imagined walking within a specific environment and reported that brain activity occurred in visual as well as higher order motor cortical regions. This interpretation supports the view of Ungerleider and Mishkin (1982), who state that projections arising from primary visual areas follow two distinct pathways: the ventral route involving the occipito-temporal pathway and inferotemporal cortex; and the dorsal pathway also involving the occipito-temporal pathway and posterior parietal cortex.

More recent literature suggests the same dichotomy with the ventral pathway mediating perception and the dorsal linked to action (Milner & Goodale, 1995). However, this interpretation has not identified the explicit relationship between the two pathways and VI and MI.

How are VI and MI different? According to Solodkin et al. (2004), different strategies are used for MI and VI. For example, MI is hard to verbalize whereas VI is not. MI follows the same properties of executed movements (for example they both follow Fitt's law) whereas VI does not. In other words, MI cannot overcome the limitations of executed movements whereas VI can. Also, similar physiological changes observed in executed movements are observed in MI (like increase in muscle voltage) but not in VI. The networks for the two types of imagery are found to be different when each is compared to the networks used in actual movements. MI and executed movements share several common elements which reinforces the idea that MI is truly involved with motor preparation, motor execution and motor learning. In contrast, in VI, primary motor activation and sensory activation are not present; VI relies heavily on connectivity patterns originating in the occipital areas, which supports the idea that this behavior may be classified as a visual task (see Kosslyn, Thompson, Wraga, & Alpert, 2001).

Of special interest to the present study, Stevens (2005) used a selective interference paradigm to investigate whether separate representations underlie VI and MI. Experiment 1 examined Fitt's Law across visual and motor imagery conditions to provide a baseline difference between the two modes of representation. Subjects were

asked to simulate walking along a wooden path, or imagine a black disc traversing the path. Experiment 2 used a selective interference paradigm with participants completing two tasks simultaneously – imagining one of the following: visual (a disc moving down a path), visual-motor (human walking a path) and motor (human running in place) combined with a visual (fixation), motor (stand on one leg), and visual-motor interference task. Results indicated significant increases in processing time from simultaneous inputs, compared to instances of a singular input. This was interpreted as evidence that the tasks were in competition for space on the same processing pathway. Stevens concluded, "The present set of experiments demonstrates cases of overlap between visual and motor imagery. Just as perception and action are tightly linked, so too are the counterpart representation systems" (p. 20). This paradigm has not been used in the context of perceived reach within the context of estimating distances.

One of the common issues of interest that underscores much of the literature noted and both of the experiments presented here is the "two-visual-systems hypothesis" initially advanced by Milner and Goodale (1995) (see Goodale, Kroliczak, & Westwood, 2005 for update) and recently debated by Jeannerod and Jacob (2005).

Two-Visual System Hypothesis

Although several methodological approaches have been designed in reference to understanding perceived reach, our attention is drawn to the nature of visual representation used in this event. Vision provides two important components for a successful reach. First, it specifies the fundamental object properties necessary to pre-plan the transport and the grasp component. Second, it provides consistent "online"

feedback for fine-tuning of motor output (Jeannerod, 1988). Briefly, for an action such as reaching to grasp an object, the theory holds that visual information is transformed to a 'perceptual' representation that gives meaning to the environment and object. Combined with intention for action, this information is transformed to a 'visuomotor' representation; thereby suggesting separate and distinct perceptual and visuomotor streams. According to Milner and Goodale (1995), visual processing used in programming and controlling an action is different from visual processing needed for the perception and recognition of objects. The researchers suggest that visually guided movements are mediated by visuomotor systems in the dorsal stream (e.g., Goodale, Milner, Jackobson, & Carey, 1991). The dorsal stream is a set of visual projections that start in the primary visual cortex and end in the posterior parietal cortex area. On the other hand, they also argue that the perception and recognition of objects are mediated by ventral-stream projections, which also arise in the primary visual cortex, but project into the temporal lobe. For example, patients with damage to the dorsal stream have impaired movements but demonstrate intact perception of objects (Perenin & Vighetto, 1988; Milner, Dijerkman, Pisella, McIntosh, Tilikete, Vighetto, & Rossetti, 2001). However, a more recent update of the perception/action model (PAM), suggests that the ventral and dorsal streams interact (couple) to enhance optimal behavior. This idea in general reflects the contemporary view of the "two-visual system" recently updated by Goodale, Westwood, & Milner (2004).

More evidence for distinctive visual pathways for perception and action has been reported with normal subjects. For example, the scaling of grip aperture in prehension is

influenced by the size of the object, but remains unaffected by size-contrast illusions that influence perceptual judgments of the size of the object (Carey, 2001). According to this account, size-contrast illusions only affect perception and not action because the ventral and dorsal streams compute different types of information about the object. Moreover, the perception and the action streams are speculated to operate under very different temporal constraints. According to Milner and Goodale (1995), perception and actions streams are contrasted in terms of their temporal properties. The dorsal pathway (specialized for the control of action) may not retain information in long-term memory and operates in real-time only (Goodale, Jackobson, & Keillor, 1994; Graham et al., 1998; Hu, Eagleson, & Goodale, 1999). The dorsal stream is thought to process extrinsic information like distance and direction of objects that change regularly over time. In contrast, the ventral stream (specialized for perception) retains information over time). This stream is thought to process intrinsic information such as the shape and size of the object that remain relatively constant over time.

An interesting approach to investigate the nature of visual representation in action control and in this case imagery is to introduce a temporal delay between stimulus presentation and response. This paradigm has been used in pointing tasks (Bradshaw, Watt, Elliot, & Riddell, 2004; Bradshaw & Watt, 2002; Elliot & Madalena, 1987; Heath, Westwood, & Binsted, 2004; Westwood, Heath, & Roy, 2003) and prehension tasks (e.g., Hu et al., 1999). Experimentally, the use of a temporal delay has been shown to modify the features of visuomotor responses. For example, Bradshaw & Watt (2002) found that a two-second delay is sufficient to disturb significantly prehensile movement.

They found that when presented with a delay, subjects exhibited reaches with lower peak velocities and lower peak apertures. Moreover, they used a perceptual-matching condition and found that accuracy, as well as variance, of a pointing task remained unaffected after imposing a temporal delay. Those findings support the notion that the visuo-motor pathway has limited memory and that response after a temporal delay may be sustained by representation stored in memory through the perceptual stream.

As mentioned before, perceptual tasks (e.g. recognizing the color of a target) have been separated from action-based tasks (e.g. reaching for an object) and differences in performance have been explained by functional dissociations of two independent streams, the ventral and the dorsal stream located in the temporal and parietal lobes, respectively. Several behavioral experiments have demonstrated that some patients can perform perceptual tasks but not visually- guided behavioral tasks (see, Goodale et al, 1994); on the other hand, others are capable of performing normally on visuo-motor tasks, but not perceptual tasks (see Goodale et al, 1991).

Statement of Purpose

The primary intent of the present study was to explore fundamental questions about the role and relationship between motor and visual imagery within the context of estimating reach. That is, does VI and MI operate in similar, separate, or parallel streams? Stated differently, are perceptual and biomechanic representations processed in similar, separate, or parallel VI and MI processes? And if the two streams are in fact separate, how are visual representations transformed into MI? How accurate are we at perceiving reachability under a VI paradigm, assuming that VI does not account for

biomechanical constraints? Is MI affected by response-delay, similar to how actual movement is affected by pre- movement-delay? Does reaching accuracy under VI remain unaffected by response-delay?

To address these questions, two experiments were designed. Experiment 1 examined the effect of interference on perceived reach while executing visual and motor imagery tasks. More specifically, with this experiment we wished to (a) delineate the differences in estimating reaching distances between use of VI and MI under matched environmental conditions, and (b) explore the dissociations and commonalities between the two visual modes by including a selective interference task. Experiment 2 investigated the effect of response-delay on estimation of reach. *This tactic has been used (as pre-movement delay) in several studies of movement execution but it is unique to imagined action research*. When considered together, we anticipated that the results of these experiments would provide new insight into the use of visual information with the programming of imagined and real movements.

CHAPTER II

STUDY 1 – INTERFERENCE EFFECTS

Introduction

The aim of Experiment 1 was to examine and compare visual imagery (VI) and motor imagery (MI) tasks under matched environmental conditions to explore the distinction and cooperation of the visual and motor systems in representing actions. Arguably, in the paradigm of imagined reach, both VI and MI are processing channels. As noted earlier, MI is defined as a dynamic state during which an individual mentally simulates a specific motor action (Decety, 1996). This definition implies that the subject "feels" himself/herself moving – which is a critical methodological tactic in imagined versus actual movement research. In order to infer a high correlation with actual movements, MI must be sensitive to the biomechanical constraints of the task (e.g., muscle force and joint angle) (Jeannerod, 1999; Johnson, 2001). On the other hand, VI involves perceived elements of the environment such as object location and size of the path. According to Stevens (2005), the relationship between the two has received little attention, which underscores the aim of this experiment, *which is, to compare imagined reach responses in conditions of VI and MI in different paradigms (no interference, interference with a motor task, and interference with a visual task).*

Stevens addressed this issue through a series of behavioral paradigms using imagined movement times and selective interference effects in an attempt to understand the cognitive processes underlying visual and motor imagery. Experiment 1 examined Fitt's Law across visual and motor imagery conditions to provide a baseline difference

between the two modes of representation. Subjects were asked to simulate walking along a wooden path, or imagine a black disc traversing the path. Experiment 2 used a selective interference paradigm with participants completing two tasks simultaneously – imagining one of the following: visual (a disc moving down a path), visual-motor (human walking a path) and motor (human running in place) combined with a visual (fixation), motor (stand on one leg), and visual-motor interference task. Results indicated significant increases in processing time from simultaneous inputs, compared to instances of a singular input. This was interpreted as evidence that the tasks were in competition for space on the same processing pathway. The researcher found that VI was mostly used in order to represent perceived characteristics of the environment, such as object size; whereas MI was used to generate representations of "biomechanic-specific" features, such as human muscle force. The interference effect, which included a motor task performed simultaneously with the VI paradigm, or a visual task performed with the MI paradigm, confirmed separate cognitive processes for visual and motor representation modalities.

The design of our experiment also included a selective interference tactic where subjects completed two tasks at the same time. The interference paradigm was modified from Stevens: we added a visual task to the MI task and a motor task to the VI condition. We predicted that if the two visual streams are in fact dissociated, then the interference task should not affect the performance of the participant. Significant increases in the number of errors or direction of error (mean bias) would be interpreted as evidence that the two tasks are in competition for space on the same processing pathway. Here

imagined reachability estimates were measured across four conditions: VI (visual imagery), MI (motor imagery), VI and MI with *motor interference* and VI and MI with *visual interference*. Significant increases in the number of errors or estimation bias was expected when the modalities for the imagined task and the interference task were matched. Given the assumption that the ventral stream is "metrically" challenged and the dorsal stream is a "metrically" accurate stream (Goodale & Humphrey, 1998), we predicted that participants would make more errors in VI compared to MI. Borrowing from previous literature (Bootsma, Bakker, Snippenberg & Tdlohreg, 1992; Carello, Grosofsky, Reichel, Soloan, & Turvey, 1989; Fisher, 2000, 2005; Heft, 1993; Mark, Nemeth, Gardner, Dainoff, Duffy, & Grandt, 1997; Robinovitch, 1998; Rochat & Wraga, 1997) we speculated that participants would overestimate in the MI condition. Also, we were tempted to predict that the overestimation bias for VI would be increased because the biomechanic representation of the movement would not be present.

Methods

Participants

Participants included 29 (15 males and 14 females) right-handed volunteers between the ages of 19 to 23 years selected from a Motor Behavior Subject Pool at Texas A&M University. All participants were screened using a questionnaire to ensure that none had a history of past or present sensorimotor impairment. For the purposes of this study, only subjects identified as strong right-handers (i.e., those for whom all items scored in that lateral direction using the Lateral Preference Inventory Questionnaire [Coren, 1993]) were included in the investigation. All subjects signed informed consent

forms approved by our Institutional Review Board (IRB) before beginning the experiment and were naïve to the hypotheses under investigation prior to the study.

Apparatus

A general illustration of the testing apparatus used to solicit perceived and actual reaching behavior is shown in Figure 1. Peer review of this setup has been conducted (Gabbard, Ammar, & Rodrigues, 2005a,b,c,d). Using a projection system linked to a personal computer (PC) programmed with Q-Basic software, visual images were systematically projected onto a table surface at the individual's midline (90^{o}) position. The table was constructed on a sliding bracket frame, allowing it be moved back and forward for adjustment to the participant; table height was fixed at 74 cm. Participants sat in an adjustable ergonomics chair fixed to the floor, aligned with the midline of the table and projected image midline, and set at a fixed height of 44 cm from the top of the seat pan to the floor. Table and chair height were adopted from Carello et al. (1989) and Heft (1993). A modified commercial seatbelt system, attached to the back of the chair at the upper torso level, was used to establish reaching limitations. The room was darkened with the exception of light from the computer monitor and white visual images projected onto the table programmed with a gray background surface. As noted earlier, our lab confirms that this setup afforded accurate measurement of actual and imagined reaching responses relative (scaled) to each participant.

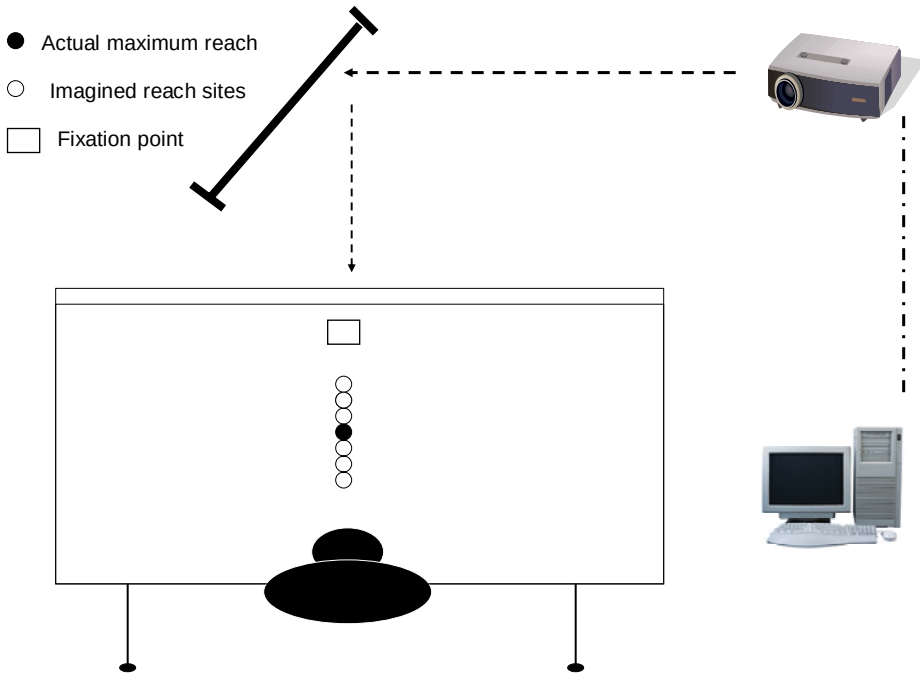

Figure 1. General experimental paradigm.

Procedure

To begin, participants were systematically positioned in the ergonomic chair and introduced to the task for determining 'actual' maximum reach –fully extending their right limb and middle finger to pull back a penny using a 1-*df* reach (Carello et al. 1989). Based on the actual reach measurement, seven imagined target presentations were randomly programmed with "4" being the actual reach complemented with three image sites above and three below – 2 cm apart; 5 trials were given at each site. In the imagined condition subjects were asked to kinesthetically 'feel' themselves executing the

movement with the right limb – therefore being more sensitive to the biomechanical constraints of the task (Jeannerod, 1999; Johnson, et al., 2001).

For MI trials, the dominant (right) hand was placed within a drawn box on the table close to the torso at midline while the non-dominant limb rested on the participant's upper left thigh under the table. For VI trials, both limbs rested on the participant's lap under the table. For VI trials, both limbs rested on the participant's laps under the table. In this condition, we encouraged participants to disengage their own hand by instructing them to give a *visual estimate* of whether the target was reachable or not. We hypothesized that thinking about one's own hand would prompt motor simulation (MI) processes where participants would be more sensitive to the biomechanic parameters of the reaching movement. On the other hand, visual estimation (hands placed on the lap under the table) would most likely activate ventral pathways and hence be less sensitive to biomechanic considerations (adopted from, Sirigu & Duhamel, 2001). Testing required six 20-minute sessions (within two weeks); one for each condition. Six blocks of trials (conditions) were used: MI, VI, MI with visual interference (MV), MI with motor interference (MM), VI with motor interference (VM), and VI with visual interference (VV). The visual interference task involved subjects fixating on a screen positioned at the end of the table while imaging the movement. Random block letters were projected for 500ms. The motor interference task consisted of subjects taping with their right foot (complementary lateral action) when they heard the first beep (before the target came up) until the target went away. Conditions were counterbalanced between subjects and stimulus presentation was given in random order,

following three practice trials (per block). Data collection began with a 5 s "Ready!" signal – that was immediately followed by a central fixation point lasting 3 s, at the end of which the participant heard a beep. The image appeared immediately thereafter and lasted for 500ms* [this speed was determined as the result of pilot-testing units in the range of 150ms to 2s] after which a second audible 'beep' provided the signal for the participant to respond. The participant was instructed to respond immediately with a "Yes" or "No" in reference to whether the stimulus was "reachable" or not. After each target presentation, the experimenter asked the subject the following question: "Is the target reachable?" No feedback was available to participants about the accuracy of their performance.

Data Analysis

The focus of analysis was to determine each participant's accuracy in estimating whether or not each of the seven randomly presented 'imagined' stimulus targets were reachable or not; as noted by a "Yes" or "No" response. The basis for being reachable was derived from the participant's actual reach at the midline position using the right (dominant) limb. Chi-square procedures were used to compare the six conditions in regard to total error, distribution of error across targets, and distribution of error between target responses. Descriptive statistics and analysis of variance (ANOVA) procedures with Duncan's post hoc tests were employed to determine estimates of error in terms of mean bias in cm; mean bias is defined as the general direction of error (i.e., over- or underestimation). That is, data were given a positive or negative sign and then summed

to provide a signed mean. All tests of significance were based upon an alpha level of .05.

Results

The first step in the analysis was to look at MI and VI under matched environmental conditions. These data revealed that the paradigm used in the context of perceived reach was effective and provided a baseline distinction between the two modes of representations.

MI vs. VI (Baseline)

Total error represented the percentage of wrong responses in relation to total trials for MI and VI conditions. That is, when participants responded "no" when actually the target was within reach, or "yes" when in fact, the target was out of reach. Figure 2 shows the general response profiles for participants by condition – in this case, percent error in relation to total trials. Chi-square analysis indicated a significant baseline difference between MI and VI ($\chi^2 = 3.85$, $p <. 05$), with fewer errors in the MI condition.

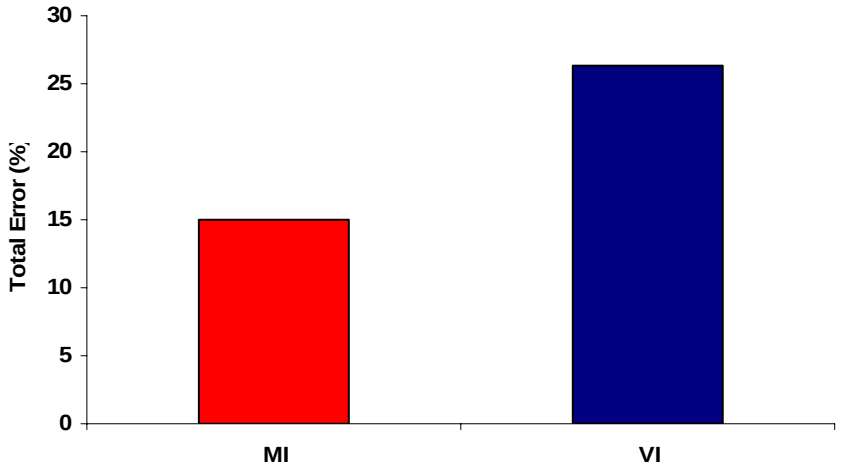

Figure 2. Total error (%) for MI and VI baseline.

In reference to the distribution of error (Fig. 3), although the general level of accuracy for both conditions was relatively high, with overall error only about 15% for MI baseline and about 26% in the VI condition, our attention at this point focused on where the errors occurred. The reader should keep in mind that there were seven targets presented at the midline position with "4" representing the participant's actual maximum reach. Incorrect responses at the three targets above (5-7) the actual target were considered an overestimation. Incorrect responses at the four targets below (1-4) the actual target were considered an underestimation. For example, if a participant noted that target 5 was reachable ('yes') when in fact it was not, it was an overestimation. The highest frequency of error occurred around target 4 for both MI and VI at a value of about 34% and 54% respectively. Chi-square analysis between targets indicated a

significant difference between MI and VI at target 3 ($\chi^2 = 19.83$, $p <. 001$) and at target 4 ($\chi^2 = 8.11$, $p <. 01$). In essence participants were underestimating perceived reach with both MI and VI with a highest rate of "No" responses in VI.

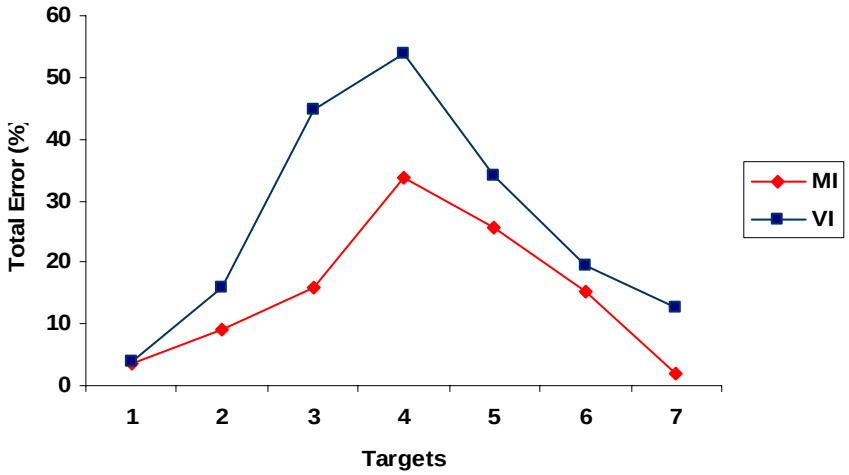

Figure 3. Distribution of error for MI and VI baseline.

Needless to say, the results just mentioned are relative and a general observation. Figure 4 illustrates estimation values (mean bias) for MI and VI conditions. These values were derived from mean error in cm for each condition; from actual reach (target 4), each of the three higher (distal) and lower (proximal) targets were 2 cm apart. That is, data were given a positive or negative sign and then summed to provide a signed mean. Zero on the y-axis represents no error, while a minus value represents an

underestimation and a positive value represents an overestimation. For example, if a participant noted that target 3 was not reachable ('No') when in fact it was, it was an underestimation.

The ANOVA and follow-up procedures indicated a significant main effect of Condition, F (1, 29) = 4.27, p =.03. MI was significantly different from VI and participants slightly underestimated in both MI (-0.12) and VI (-0.27) conditions.

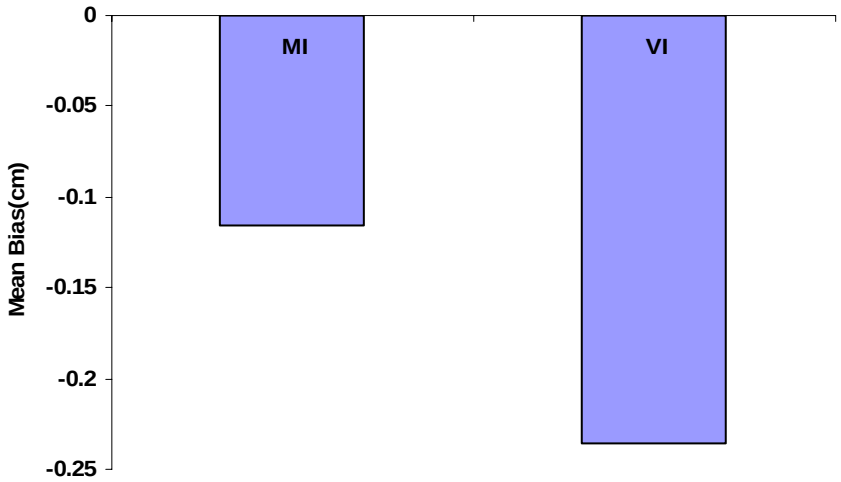

Figure 4. Mean bias (cm) for MI and VI baseline.

MI with Interference

In reference to total error (Fig. 5), chi-square analysis indicated no overall difference between MI and MV (χ^2=0.23, *p=.70*). However, when comparing MI and

MM, an overall difference ($\chi^2 = 4.68, p \leq 0.05$) was found. Participants exhibited more error in the MM condition (around 27%) as compared to the MI responses (around 15%).

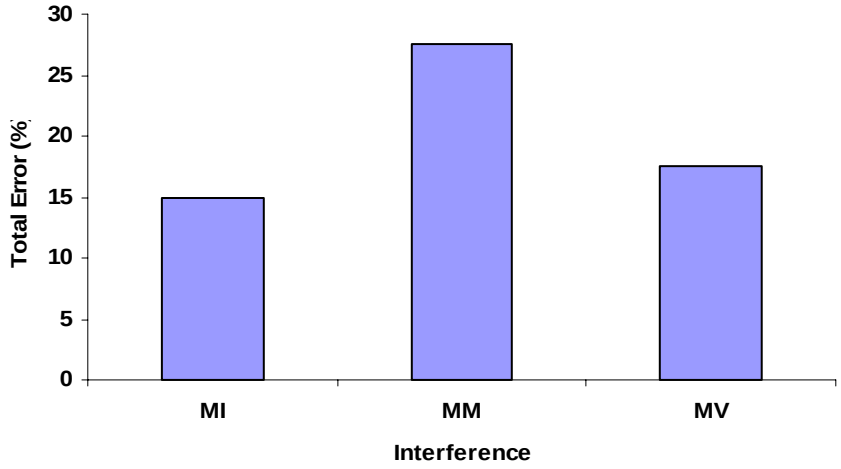

Figure 5. Total error for MI interference condition.

An observation of the distribution of error across targets (Fig. 6) noted that the highest frequency of error occurred in the MM condition around target 4 at a value of about 80%. Most of the errors for the MV condition occurred around target 4 and 5 at a value of about 50%. At a lesser extent (about 33%), target 4 presented peak error for MI. Analysis between targets indicated a significant difference between MI and MV ($\chi^2 = 17.39, p < .001$), MI and MM ($\chi^2 = 13.26, p < .001$) and MM and MV ($\chi^2 = 48.44, p < .001$) at target 3. Also, a significant difference between MI and MV ($\chi^2 = 4.63, p <$

05), MI and MM (χ^2 = 5.77, *p <. 025)* and MM and MV (χ^2 = 20.05, *p <. 001)* was found at target 4.

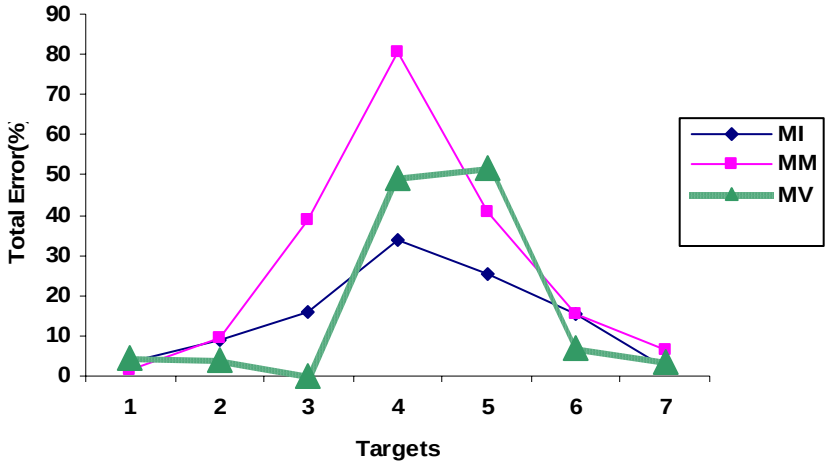

Figure 6. Distribution of error for MI interference condition.

Figure 7 illustrates estimation values (mean bias) for conditions. ANOVA results indicated a significant main effect of Condition, *F* (2, 29) =9.97, p<. 001. Post hoc analysis (Duncan's) revealed that MI was different then MM but not MV. As shown in the figure, participants slightly overestimated in the MV condition and slightly underestimated in MI (-0.12) and MM (-0.28). Note that the largest underestimation was made in the MM condition.

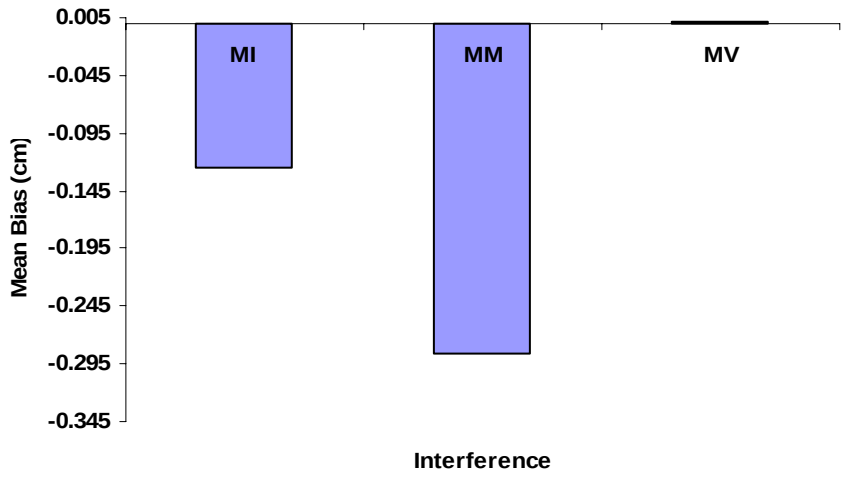

Figure 7. Mean bias (cm) for MI interference condition.

VI with Interference

In reference to total error (Fig. 8), chi-square analysis indicated no overall difference between VI and VM ($\chi^2 = 2.39$, $p = .17$). However, when comparing VI and VV, a significant effect of interference was found ($\chi^2 = 4.43$, $p \leq .05$). Participants exhibited most of the errors in the VV condition (around 40%) as compared to VI (around 26%) and VM (around 17%).

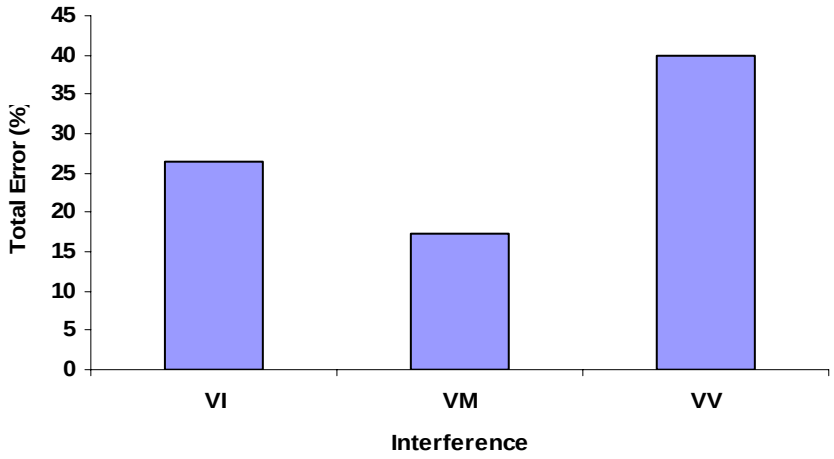

Figure 8. Total error (%) for VI interference condition.

Analysis of the distribution of error (Fig. 9), revealed that the highest frequency of error occurred in the VV condition around target 3 at a value of about 76%. Most of the errors for the VI and VM conditions occurred around target 4 at a value of about 55%. Analysis between targets indicated a significant difference between VI and VV ($\chi^2 = 20.10$, $p \leq .001$) and VM and VV ($\chi^2 = 37.28$, $p \leq .001$) at target 3.

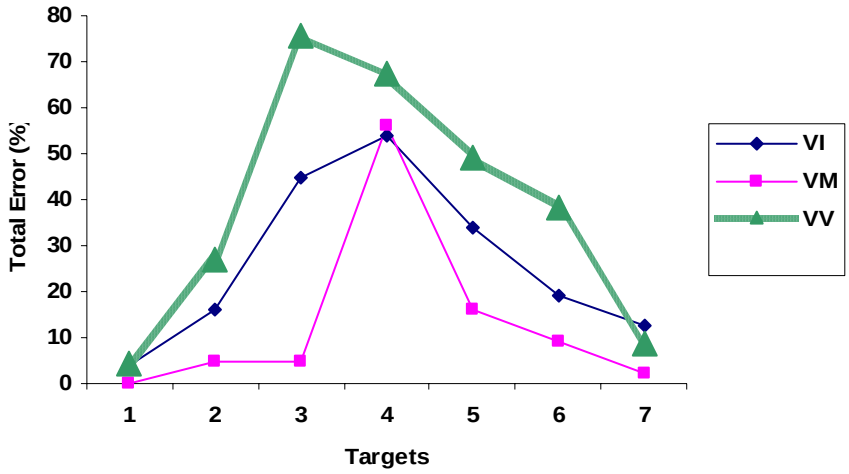

Figure 9. Distribution of error for VI interference condition.

In regard to mean bias (Fig. 10), ANOVA results revealed a significant main effect of Condition, F (2, 29) =2.99, $p \leq .05$. Follow-up indicated that VI was not significantly different from VM but, that VI and VM were significantly different fromVV. Participants underestimated in all three conditions with VI (-0.27), VM (-0.27) and VV (-0.46).

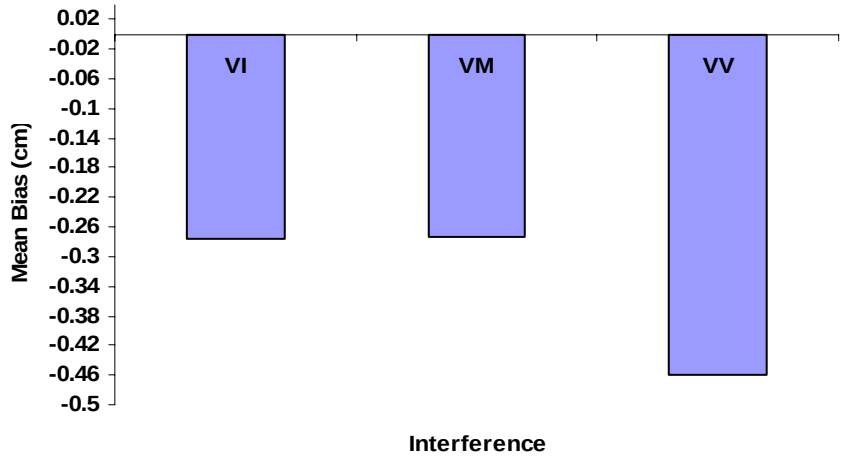

Figure 10. Mean bias (cm) for VI interference condition.

Discussion

Our intent in Experiment 1 was to investigate estimated (imagined) reach responses in conditions of VI and MI in different paradigms: no interference, interference with a motor task, and interference with a visual task. More specifically, we wanted to answer the following questions: *Does VI and MI operate in similar, separate, or parallel streams? Stated differently, are visual and biomechanical representations processed in similar, separate, or parallel VI and MI processes? And if the two streams are in fact separate, how are visual representations transformed into MI? How accurate are we at perceiving reachability under a VI paradigm, assuming that VI does not account for biomechanical constraints?*

Baseline Data

In reference to the baseline data (VI vs. MI), total error results indicated that the general response profiles for the two conditions were significantly different with less error in MI compared to VI. Further analyses to determine the distribution and direction of error, revealed that condition responses were different with higher error rates in VI. Most errors occurred around target 4; keeping in mind that target 4 represented actual maximum reach. In view of the general direction (mean bias) of error, although the analyses indicated that MI responses differed from VI, the margin of error was quite small for both conditions (-.12 cm for MI and -.24 cm for VI). When viewing the response profiles across both conditions, the general tendency was to underestimate; that is, answer 'No' when the target was in fact reachable. Once again, the margin of error from the actual target was small especially in MI, which gives further indication of the superiority of MI compared to VI in the context of perceived reach.

From these results two key observations directed our attention. First, was the fact that participants were consistently better in MI compared to VI. And second, was the observation that participants underestimated in both conditions. In regard to the first observation, although perception of reachability for both MI and VI was restricted by the same spatial parameters of the perceived environment, the translation of this information within each modality seems to be different. It appears that our results approximate those reported by Solodkin et al. (2004), suggesting the use of different networks for MI and VI. In fact, the researchers concluded that MI follows very similar processes comparable to executed movements (e.g. Fitt's law) whereas VI does not. Furthermore,

the networks for the two types of imagery were found to be different when each is compared to the networks used in actual movements. In fact, as noted earlier, MI and executed movements share several common characteristics, reinforcing the involvement of MI with motor preparation, execution and motor learning.

Although our setup had no 'time' component, these results to some extent also support the conclusions of Stevens (2005) suggesting that Fitt's Law holds for MI but not for VI. In summary, representation processes used during VI seem to have preserved the spatial components of the movement while the ones used in MI appear to have translated the spatial information into human movement, therefore accounting for the constraints present within the system. An interesting observation is that the errors were significantly different between MI and VI only around target 3 and target 4. VI is less accurate then MI at or around critical boundary. Further research would be needed to better understand this trend.

The baseline differences found between MI and VI appear to complement the views of Milner and Goodale (1995) stating that the visual processing used in programming and controlling an action are different from the ones needed for the perception and recognition of objects. The researchers suggested that visually guided movements are mediated by visuomotor systems in the dorsal stream (e.g., Goodale et al., 1991). On the other hand, they argued that the perception and recognition of objects are mediated by ventral-stream projections. In line with our data and previous literature, it is reasonable to conclude that MI is relying on the dorsal stream which is "metrically"

more accurate, whereas VI is relying on the ventral stream which is metrically challenged (Milner & Goodale, 1995).

Regarding the second observation, we initially predicted overestimations in both MI and VI with greater overestimation values in VI. For MI, the literature reports overestimation at the midline position; for reviews of theories discussing the overestimation bias see Fischer (2000) or Gabbard et al., (2005a). In the present experiment, viewing time (total time that participants could see the target) was 500 ms as opposed to other experiments reporting overestimations with viewing time ranging from no time to 2 s. For example, in the case of Gabbard et al. (2005a), a similar experimental paradigm was used, but with a shorter viewing time (150 ms). As it appears in the present experiment compared to the example given using a different viewing time, participants were closer to actual reach but more conservative with longer viewing time. Obviously, future research needs to examine the influence of viewing duration on perceived reach.

For VI, the underlying assumption for overestimation was that biomechanical constraints were not accounted for which in turn would generate a less conservative, more confident approach. However this prediction fell short given the underestimation values. Our results might be explained by the fact that participants were counterbalancing for the lack of biomechanical information by being over conservative in their response and therefore leading to increased underestimations.

This phase of Experiment 1 provided a baseline difference between MI and VI. However, the question about whether the cognitive processes mediating these two types of imagery are distinct should be addressed.

Interference Conditions

A selective interference paradigm was used in the next phase of experiment 1 in order to examine whether distinct cognitive processes underlie VI and MI. In this type of paradigm, participants were asked to complete two tasks simultaneously. Previous research reported that processing time for a spatial task is not affected by a verbal (Brooks, 1967) or visual (Baddeley & Lieberman, 1980) input presented at the same time because the two pieces of information apparently activate separate cognitive pathways. According to Stevens, "if the same cognitive operation must process a piece of information, such as two independent visual inputs, there is channel interference or build-up and a significant delay in processing time results" (p. 10). Consequently, we hypothesized that increased errors in perceived reach resulting from simultaneous inputs would be interpreted that the two tasks are competing for space on the same processing channel.

In reference to MI, total error indicated no significant difference between MI and MV, but a significant difference between MI and MM. Participants in the MI condition were more accurate then in the MM condition. When the motor interference (foot tapping) was introduced, the accuracy of perceiving reachability was reduced. That is, the same cognitive pathway had to process both information (MI and foot tapping simultaneously) and therefore affected the accuracy of the response profile. Further

analysis to determine the distribution of errors in the MI interference task indicated that the highest frequency of error occurred in the MM condition around target 4. In regard to the interaction found at target 3 and target 4, we may speculate from a dynamical systems perspective that the system is relatively unstable around the critical boundary and may need to rely on both streams when deciding whether the target is reachable or not This interaction is not found around target 5 and might be explained by the possibility of the system regaining flexibility after crossing the critical boundary. In view of the general direction (mean bias) of error, although the analyses indicated that MM responses differed from MI and MV (which were not distinct from each other), the margin of error was quite small – about -0.25 cm from actual target. The small margin of error from actual target gives further indication of the relatively effective use of MI in conditions of MM, MV and MI.

In regard to VI, total error indicated no significant difference between VI and VM, but a significant difference between VI and VV was found. Participants in VV produced more error compared to VI and VM. The increase in error in VV was expected because the interference task taxed the visual channel. In view of the distribution of error, the highest rate of error occurred in the VV condition around target 4. Most of the error for VI and VM also occurred around actual reach but to a lesser extent. Mean bias results indicated that participants underestimated in all three conditions with the highest underestimation in VV (-0.46). Analysis between targets indicated a significant difference between VI and VV and VM and VV at target 3. This significant difference

around critical boundary may again be explained as a phase of instability and possibly the convergence of the two streams.

Overall, it appears that participants were more conservative and less confident in perceiving reachability when an interference task was introduced. The load on the visual system (having to visually perceive the target and keep track of the letters presented on the screen) and the motor system (having to motor image the reaching movement and tap with the right-foot) may have generated an attentional load that may have induced more conservative (less confident) responses.

Similar results for both motor and visual interference were reported by Stevens using three movement tasks: visual (DISC moving down the path), motor (RUN in place 25 steps) and visual-motor (WALK down the path). Imagined DISC movement times were found to be significantly longer in the visual interference condition and visual-motor condition and imagined RUN times were significantly longer in the motor interference condition and visual-motor condition. VI was presumably used to represent the spatial coordinates of the task while MI most likely represented the biomechanical constraints of the task. The patterns of interference effects show that VI and MI tasks most likely operate within distinct processing mechanisms. An important point of interest regarding Stevens studies (experiment 2) is that both of the motor tasks used (RUN and WALK) involved the use of the legs. In experiment 3, the researcher explored the question of whether distinct cognitive motor imagery processing can be made in terms of biomechanic specific tasks. Two different motor tasks were used (running in place and clapping in place) in both biomechanically related and unrelated

selective interference conditions (leg-up and arm-up). Imagined movement times were found to increase significantly when the interference task and the imagery task involved similar biomechanic demands. Unrelated interference tasks did not seem to affect imagined movement times. The author concluded that biomechanic specific processing occurs during motor imagery.

Our results do not agree with the findings of Stevens where only related interference tasks affected imagined movements. Although, the interference task used in our paradigm (foot tapping) was unrelated to the imagined motor task (imagined reaching), we did find that participants exhibited more errors in MM compared to MI. This discrepancy in results may be related to the nature of the tasks and the paradigm. To our knowledge, this is the first study investigating MI and VI in the context of perceived reach.

The underestimation findings found for *MI, MI interference*, *VI, and VI interference*, lend additional support to our earlier suggestions that perceived reach includes considerations of perceived ability and perceived task demands (Gabbard et al., 2005a). In our conclusions and those of Robinovitch (1998) and Carello et al. (1989), the word *confidence* is used in association with perceived reach. We suggest that confidence, in this context, is a *cognitive state* based on perceived ability and perceived task demands. It seems reasonable to suggest that building up the system such as in the interference tasks paradigm used might significantly decrease our perceived ability and increase the perceived task demands and in turn a decrease in the confidence level results .Future extensions of this work should consider further examination of the

confidence notion – especially as it relates to the developmental aspects of reaching behavior.

As mentioned earlier, VI is most likely used to represent spatial parameters (such as distance and size of target) while MI is most likely used to represent the biomechanic constraints of an action (such as muscle force and joint torque). Keep in mind that the biomechanical parameters are processed relative to the spatial elements of the task (reaching in this case) and therefore MI depends heavily on VI for recognition of the spatial constraints in the environment. Several studies have demonstrated separate patterns of brain activity associated with rotations tasks. For example, Kosslyn, Thompson, Wraga, & Alpert, (2001) reported that rotation of objects are primarily associated with occipital and parietal areas, whereas rotation of humans hands or objects held by human hand activated motor areas including the primary motor cortex. Recent neuropsychological studies show that imagined object rotation may be considered a visual imagery task and is processed in the right hemisphere, whereas hand rotations may be considered a motor imagery task and is processed in the left hemisphere (Tomasino & Rumiati, 2004).

In summary, it appears that MI and VI, in the context of perceived reach recruit different processing mechanisms. The interference effects used in Experiment 1 demonstrate that motor tasks interfere with the ability to MI whereas visual tasks interfere with the ability to VI. We do concede that this conclusion is limited to perceived reach tasks where the visual system would always be recruited to a certain extent because of the particular nature of the task

In regard to our initial questions relevant to Experiment 1: Does VI and MI operate in similar, separate, or parallel streams? Stated differently, are perceptual and biomechanic representations processed in similar, separate, or parallel VI and MI processes? The interference effects demonstrated separate cognitive processes mediating VI and MI. MI appears to be associated with the dorsal stream whereas VI seems connected to the ventral stream. These findings agree with the "two-visual system" theoretical model advanced by Milner & Goodale (1995), where a distinction is described between what has been called "vision for action" and "vision for perception"(p.131).

And if the two streams are in fact separate, how are visual representations transformed into MI? It appears that the mechanisms underlying VI were most likely used to perceive spatial cues such as object size and location. In contrast, MI was likely used to perceive biomechanical demands such as torque and muscle force. According to Stevens (2005), these modalities must run concurrently and concisely to produce significant representations of movements within the environment.

How accurate are we at perceiving reachability under a VI paradigm, assuming that VI does not account for biomechanical constraints? As mentioned earlier, VI and MI seem to operate in separate streams. VI is probably connected to the ventral stream which does not account for kinematic representation of movement resulting in less accurate responses in perceived reach. In contrast, MI in our experiment appears to be associated with the dorsal stream which is restrained by the kinematic demands of the movement which resulted in more accuracy in perceived reach. These findings are

supported by Milner and Goodale (1995) suggesting that the dorsal stream computes absolute metrics and uses an egocentric frame of reference and is required for accurate actions. On the other hand, they suggested that the ventral pathway uses an allocentric frame of reference and computes relational metrics, giving detailed representation of the environment.

In conclusion, VI seems to delineate relevant spatial parameters within our environment, then transfer them to MI which in turn would encode this information in terms of biomechanical possibilities for a certain movement. Just as perception and action are firmly coupled, so too are MI and VI.

CHAPTER III

STUDY 2 – DELAY EFFECTS

Introduction

The purpose of Experiment 2 was to examine the influence of temporal (time) constraints on perceived reach. A response-delay paradigm was used to further understand the nature of the visual representation used in MI and VI. In the present context, response-delay refers to the delay between stimulus presentation (visual information) and cue to respond to the reachability of the target. As mentioned earlier, this paradigm represents a unique approach to the study of imagined versus actual movement execution in the context of perceived reach. This paradigm offers an opportunity to explore the influence of time constraints on visual representation in simulating motor actions and the relationship to movement execution.

As stated before, the act of efficient reaching relies on an internal representation of space and object prior to movement onset. The presence of such representations facilitates the act of reaching for some period of time after visual feedback is removed (for example, reaching with eyes closed). Previous research suggests that prehensile movements are disrupted by removal of visual cues (e.g., longer deceleration times), but general kinematic markers remain similar to when movement is executed under normal viewing conditions (Bradshaw et al., 2004, Bradshaw & Watt, 2002, Connolly & Goodale, 1999; Jackobson & Goodale, 1991; Jeannerod, 1984).

Although the general paradigm of ‘delay’ is relatively unique in the context of perceived reach, it has been used in several studies of movement execution with adults

and children (e.g., Bradshaw et al., 2004; Bradshaw & Watt, 2002, Elliott & Madalena, 1987, Heath et al., 2004; Hu et al., 1999; Westwood et al., 2003). Common movement tasks include pointing accuracy and reaching kinematics. For example, Bradshaw and Watt (2002) found that after a pre-movement delay of 2 s accuracy of pointing to a remembered location decreased, whereas the variability remained constant. Moreover, in a 'perceptual-matching' condition the researchers found that both accuracy and variance were unaffected by delays of up to 4 s. In a subsequent study using children, a pre-movement delay of 2s was characterized by decrements in several kinematic measures (e.g., longer MT's, lower peak velocities) (Bradshaw et al., 2004). Other researchers report similar results ranging from a decrement in movement behavior at 1 s and 5s (Graham et al., 1998; Hu et al., 1999).

According to Viviani and McCollum (1983), movements of different amplitudes tend to have the same duration and this kinematic rule seems to hold in imagined movements. For example, subjects take the same amount of time to write small or large signature mentally. Viviani and Stucchi (1992) explain this as perception being constrained by motor schemas, which represent the implicit knowledge of the central nervous system concerning the constraints of the movement. If this explanation is correct then the kinematic rules governing actual movements should also control imagined movements (Jeannerod, 1995). In this case, we should see an increased frequency of error in imagined movements when a delay is introduced, comparable to the kinematic decrements reported by Bradshaw et al, (2004) and Bradshaw & Watt, (2002).

According to Goodale et al. (2004), visuomotor processes responsible for action control (and used in MI) do not seem to retain memory information about the target. Therefore, MI after a delay would seem to depend on information derived from early perceptual processing in the ventral stream. Given the assumption that imagined and real movements follow similar (corollary) neurocognitive paths, we predicted that response-delay would show a similar profile as shown in studies of movement execution (e.g., Bradshaw, 2004). That is, at some point, introducing a delay will adversely affect estimates of reachability. On the other hand, if the relationship is not found, more credence could be given to the notion of dissociation between imagined and actual movements. Given the assumption that the system involved in visuomotor control has only limited memory, we predicted that performance of reachability after a delay may rely on the ventral (perceptual) stream. To test this assumption, we decided to include a VI condition with a similar response-delay paradigm. Given the assumption that the ventral stream is "metrically" challenged and the dorsal stream is a more "metrically" accurate stream (Goodale & Humphrey, 1998), we predicted that participants would make more errors under VI compared to MI.

Based on results from Experiment 1, we predicted that participants would underestimate in both MI and VI with greater underestimation values in VI. In addition, given the theoretical and empirical basis for the experiment, we expected that accuracy in the MI task would decrease after a 2 s delay, whereas error in the perceptual condition (VI task) would remain constant when a delay was introduced.

Methods

Participants

Participants were 30 male and female right-handed volunteers between the ages of 19 to 23 years. All participants were screened using a questionnaire to ensure that none had a history of past or present sensorimotor impairment. For the purposes of this study, only subjects identified as strong right-handers (i.e., those for whom all items scored in that lateral direction using the Lateral Preference Inventory questionnaire [Coren, 1993]) were included in the investigation. All subjects signed informed consent forms approved by our Institutional Review Board before beginning the experiment and were naïve to the hypotheses under investigation.

Apparatus

The same testing apparatus was used as described for Experiment 1.

Procedure

To begin, participants were systematically positioned in the chair and introduced to the task for determining 'actual' maximum reach - full extension of the right limb and middle finger to pull back a penny using a 1-*df* reach (Carello et al. 1989). Based on the actual reach, seven imagined target presentations were randomly programmed with "4" being the actual reach complemented with three image sites above and three below – 2 cm apart; 5 trials were given at each site. Testing required four 20-minute sessions (within one week); two for each time condition.

In the MI condition subjects were asked to kinesthetically 'feel' themselves executing the movement with the right limb – therefore being more sensitive to the biomechanical constraints of the task (Johnson, et al. 2001). For MI trials, the dominant

(right) hand was placed within a drawn box on the table close to the torso at midline. The non-dominant limb rested on the participant's upper left thigh under the table. For VI trials, both limbs rested on the participant's laps under the table. In this condition, we encouraged participants to disengage their own hand by instructing them to give a *visual estimate* of whether the target was reachable or not. We hypothesized that thinking about one's own hand would prompt motor simulation (MI) processes where participants would be more sensitive to the biomechanic parameters of the reaching movement. On the other hand, visual estimation (hands placed on the lap under the table) would most likely activate ventral pathways and hence be less sensitive to biomechanic considerations (adopted from, Sirigu & Duhamel, 2001).

Eight blocks of trials (conditions) were used: *no-delay* with *MI (M0)*, *1* s-*delay* with *MI (M1)*, *2 s-delay* with *MI (M2), 4 s-delay* with *MI (M4), no delay* with *VI (V0), 1s-delay* with *VI (V1), 2 s-delay* with *VI (V2), and 4 s-delay* with *VI (V4)*. Conditions were counterbalanced between subjects and each condition began with three practice trials. Data collection began with a 5 s "Ready!" signal – that was immediately followed by a central fixation point lasting 3 s, at the end of which the participant heard a first beep. The image appeared immediately thereafter and lasted for 500 ms (adopted from Bradshaw & Watt, 2002). All targets were presented in a random order. A second audible 'beep' then provided the signal for the participant to respond. In the no-delay conditions, participants were instructed to respond immediately with a "Yes" or "No" in reference to whether the stimulus is "reachable" or not. No feedback was available to

participants about the accuracy of their performance. In the delay conditions, the second auditory beep signal sounded following respective delays of 1s, 2 s or 4 s.

Data Analysis

The focus of analysis was to determine each participant's accuracy in estimating whether or not each of the seven randomly presented 'imagined' stimulus targets were reachable or not as noted by a "Yes" or "No" response. The basis for being reachable was derived from the participant's actual reach measurement at midline position using the right (dominant) limb. Chi-square procedures were used to compare the six conditions in regard to total error, and distribution of error across targets. Descriptive statistics and analysis of variance (ANOVA) procedures with Duncan 's post hoc tests were employed to determine estimates of error in terms of mean bias in cm; mean bias represented the general direction of error (i.e., over- or underestimation).

Results-MI Conditions

Total Error

Total error represented the percentage of wrong responses in relation to total trials for the six conditions. That is, when the participants responded "no" when actually the target was within reach, or "yes" when in fact, the target was out of reach. Figure 11 shows the general response profiles for participants by condition. Chi-square analysis indicated no significant difference between M0 and M1 ($\chi^2 = 0.57$, $p = 0.57$) and M2 ($\chi^2 = 3.71$, $p = 0.07$). However, when comparing M0 with M4, a significant difference was noted ($\chi^2 = 3.96$, $p \leq .05$). All other comparisons did not reach the specified level of significance ($p \geq .05$) Participants exhibited the highest rate of accuracy in M0 with about

85% correct responses. The rate of errors increased as the response delay increased (about 18 % for M1 and about 26% with M2) but did not reach a level of significance with M4 (about 27%).

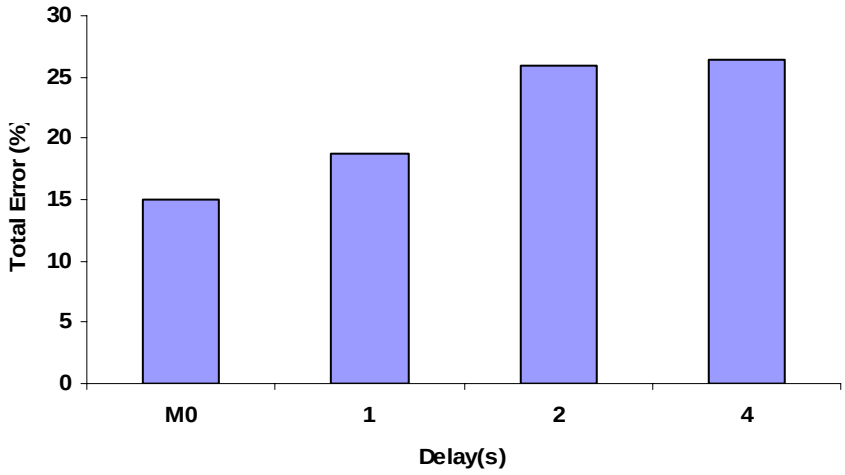

Figure 11. Total error (%) for MI conditions.

Although the general accuracy was relatively high, with overall error only about 25%, attention at this point was focused on where the errors occurred (Fig. 12.). The highest frequency of error occurred around target 4, with participants in the M0 condition exhibiting significantly fewer errors (about 34%) compared to M1, M2 and M4 (about 80%).

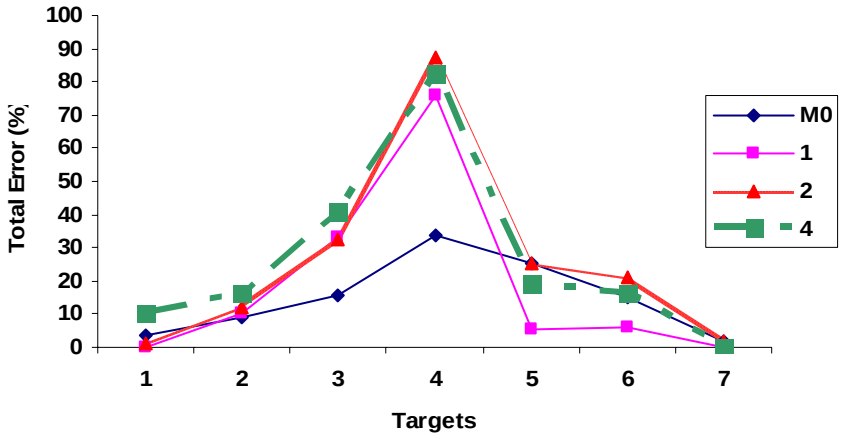

Figure 12. Distribution of error for MI conditions.

Mean Bias (cm)

ANOVA procedures revealed a significant main effect of Condition, F (3, 29) = 14.61, p <. *0001* (Fig. 13). Follow-up analysis indicated that M0 was significantly different then the three remaining conditions. Furthermore, MI with 1 s-delay was not different from M2 but both were different then M4. Overall, participants underestimated in all four conditions with M0 (-0.12), M1 (-0.44), M2 (-0.34) and M4 (-0.57). Note in Figure 13 that the largest underestimation was made in the M4.

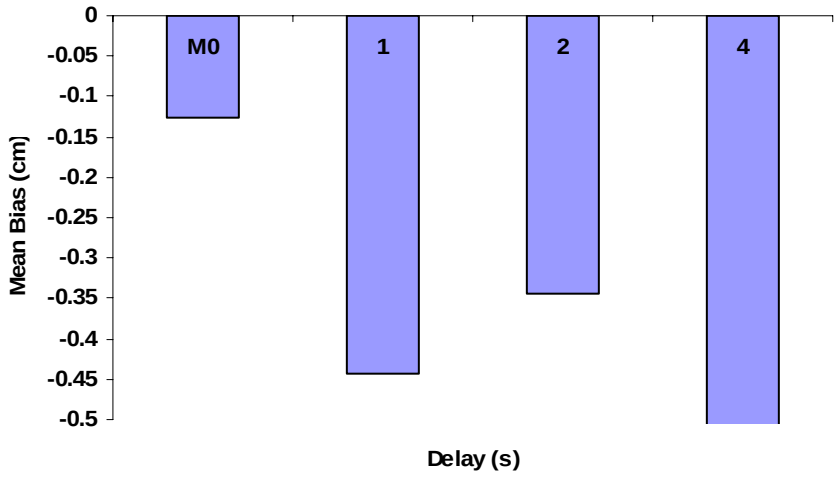

Figure 13. Mean bias (cm) for the MI conditions.

Results-VI Conditions

Total Error

Chi-square analysis indicated no overall differences between V0 and V1 (χ^2 = 0.2*, p = .74*), V2 (χ^2 = .11, *p = .87*) and V4 (χ^2 = .24, *p = .74*). Total error in each condition was V0 (26%), V1 (24%), V2 (24%), V4 (23%).

Distribution of Error

Although the general level of accuracy was still relatively high, with overall error only about 26%, our attention at this point focused on where the errors occurred. The highest frequency of error occurred around target 4 at an overall rate of around 50%. Note that this result is similar to the MI conditions, but with significantly less errors in VI conditions when a delay was introduced *($p \leq .001$).*

Mean Bias

The ANOVA revealed no distinction (main effect) of Condition, F (3, 29) =.33, p =.80. Post hoc analysis indicated that V0 was not significantly different from V1, V2 and V4, and no difference was found between all three delay conditions. Participants underestimated in all four conditions: V0 (-0.24), V1 (-0.23), V2 (-0.28) and V4 (-0.29). Once again, note that the largest underestimation was made in the V4 condition; however, the margin did not reach a level of significance.

Results-MI vs. VI Conditions

One of the underlying assumptions with Experiment 1 was that there is a baseline difference between MI and VI. Results indicated that there was a statistical distinction in which participants were more accurate in MI. Given the assumption, it also stood to reason that the comparison of M0 and V0 in Experiment 2 would be similar. In regard to total error, chi-square analysis indicated a significant baseline difference between M0 and V0 ($\chi^2 = 3.85$, $p <. 05$), with less error in the M0 condition.

In reference to the distribution of error, the highest frequency occurred around target 4 for both M0 and V0 at a value of about 34% and 54%, respectively. In essence, participants were underestimating perceived reach with M0 and V0 with the highest rate of "No" responses in V0. The ANOVA and follow-up procedures indicated a significant main effect of Condition, F (1, 29) = 4.27, $p =.04$; M0 was significantly different from V0 and participants underestimated slightly in both MI (-0.12) and VI (-0.27) conditions.

In view of combined errors for all MI-delay and VI-delay conditions**,** chi-square analysis indicated no significant differences between MI-delay and VI-delay conditions

($p \geq .05$). The profiles for the two conditions became very similar when a delay was introduced leading us to believe that the dorsal stream was no longer available for use and participants may have relied on the ventral stream.

Discussion

The present experiment was designed to examine the effect of response-delays on perceptual and visuomotor responses. More specifically, this experiment aimed to examine the role of visual representation in judgments of reachable distances. As mentioned earlier, we used a response-delay paradigm which to our knowledge represents a unique approach to the study of imagined versus actual movement execution in the context of perceived reach. The overall results of this experiment showed clearly that introducing a temporal-delay affected the ability to perceive reachibility in MI conditions, but not in VI conditions.

In reference to the MI-delay conditions, total error results indicated that the frequency of error significantly increased when a 4 s-delay was introduced; a significant difference between M0 and M4 was found. Further analyses to determine the distribution and direction of error revealed that most error occurred around target 4 with significantly more error in the delay conditions (about 80%); keeping in mind that target 4 represented actual maximum reach. In view of the general direction of error (mean bias), analyses indicated that M0 differed from M1, M2 and M4 with no difference between M1 and M2, but with both conditions being different from M4. Overall, the range of error was quite small for all conditions, with increased underestimation in the delay conditions.

In reference to VI conditions, total error results indicated no difference between V0 and VI with delay conditions (about 25%). Further analyses, revealed that most error occurred around target 4 (about 50%) across all conditions. In regard to mean bias, participants underestimated in all four conditions with no significant difference between V0 and VI with delay conditions. As shown by the data, introducing a delay to VI did not affect the accuracy of the response; overall profiles of VI conditions remained very similar across conditions.

From these results two key observations directed our attention. First, was the fact MI was affected by delay, but VI remained relatively unaffected and invariable when a delay was introduced. And second, was the observation that participants underestimated in all conditions with increased underestimations in MI-delay conditions. In regard to the first observation, although perception of reachability for both MI and VI was restricted by the same spatial parameters of the perceived environment, the translation of this information within each modality seems to be different. It appears that our results approximate those reported by Bradshaw & Watt (2002) and Bradshaw et al. (2004), suggesting that a spatial representation for perceptual-motor exists and is separate from the conventional perceptual processes. They asked subjects to grasp objects of different sizes at varying distances after delays of 1, 2 and 4 s and found that a 2 s-delay was enough to significantly affect the kinematics of a prehensile movement. Our results were very similar and consistent with the theoretical model advanced by Milner&Goodale(1995).

Regarding the second observation, based on Experiment 1, we initially predicted

underestimations in both MI and VI with greater overestimation values in VI. For MI, the literature reports overestimation at the midline position; for reviews of theories discussing the overestimation bias see Fischer (2005) or Gabbard et al., (2005a). In the present experiment, viewing time (total time that participants could see the target) was 500 ms as opposed to other experiments reporting overestimations with viewing time ranging from no time to 2 s. For example, in the case of Gabbard et al. (2005a), a similar experimental paradigm was used, but with a shorter viewing time (150 ms). In comparing that study to our use of 500ms, participants (in our study) were closer to actual reach but more conservative, meaning they were underestimating. Obviously, future research needs to examine the influence of viewing duration on perceived reach. Our data revealed that MI conditions were affected by delay resulting in increased total error and underestimation values. Those findings were consistent with our original assumption that MI likely relies on the dorsal stream and therefore operates in real time.

For VI, the underlying assumption for overestimation was based on the supposition that VI does not require biomechanical computations, leading to a less conservative approach. However this prediction fell short given the underestimation values. Our results might be explained by the fact that participants were counterbalancing for the lack of biomechanical information by being over conservative in their response and therefore leading to increased underestimations. VI-delay conditions remained unaffected when a delay was introduced which supported our original prediction.

These results are interesting not only in terms of how the memory for location operates for perceptual and visuomotor tasks but also because these data fit well with the "two-visual systems hypothesis" advanced by Milner and Goodale (1995). The researchers speculated two separate specialized pathways, one used to perceive and represent objects and the other used to act on objects. The two channels are also referred to as "perception" and "action" systems and operate under very different temporal constraints. This theory advocates that the perceptual system processes intrinsic object properties (e.g. shape and color) and represents them in a relatively stable form, which is critical in order to perceive a stable world as our body moves. In contrast, the visuomotor system operates in real-time, with no interest in the retention of object related information. Evidently, extrinsic object characteristics (e.g. distance and direction) change constantly due to ego- and object motion and therefore emphasis is given to fast computation and updating of information (Goodale, et al., 1994; Milner & Goodale, 1995).

Consistent with this, Elliot and Madalena (1987) used a pointing task to investigate the effect of pre-movement delay on the accuracy of pointing movements. They found that each delay caused an increase in error in terms of distance and therefore concluded that a representation of the environment is only available for a short period of time (< 2 s). Also, Gentillucci and Negrotti (1994) created a perceptual task where participants were asked to direct a laser pointer to the remembered location directly after target presentation. They found that pointing responses were accurate, whereas the perceptual responses generated significant overestimations of target locations.

More recently, Bradshaw and Watt (2002) and Bradshaw et al. (2004) explicitly compared perception and action responses using three different tasks: task 1 was unlit-pen pointing, where participants were asked to reach and point to the location of the target as accurately as possible; task 2 was lit-pen pointing, and task 3 was perceptual matching. They found that perception responses remained invariant with delays of up to 4 s, whereas action responses were significantly affected after 2 s. They concluded that the introduction of a temporal delay only affected the accuracy of the pointing task, but not the perceptual task. Errors in remembered location responses increased after a delay of only 2 s. In the present experiment, MI was significantly affected by a 4 s-delay as opposed to the 2 s-delay reported by Bradshaw & Watt (2002), and Bradshaw et al. (2004). This difference might be due to the nature of the task; this is the first study to our knowledge studying the effect of delays on perceived reach.

It is interesting to note that when a delay was introduced, MI profiles became very comparable to all VI profiles for total error, distribution of error and mean bias. Milner et al. (1999) found that the reaching performance of an optic ataxic patient ameliorated when a short delay was introduced which suggests that substitute representations do become accessible after a delay. Our data suggests that the alternative representations were likely drawn from the ventral (perceptual) stream because MI with delay profiles were very similar to all VI conditions. It has been shown that when a delay is introduced prior to movement onset, the response (memory-guided reaching) no longer uses egocentric frames of reference; target location is though to be computed using a scene-based frame of reference independent of the performer (Hu &

Goodale, 2000; Krigolson & Heath, 2004). In contrast, these suggestions were not be inferred by Bradshaw and Watt (2002). Here the researchers reported that when a delay was introduced to a pointing task, neither pointing accuracy nor kinematic measurements returned to baseline performance (in this study, the perceptual matching task remained invariant when a delay was introduced).

Overall, from the data presented here, it appears that the effect of a response-delay influenced accuracy of the MI (visuomotor) task, but not the VI (perceptual) task. After a 4s delay, error in MI significantly increased. Interestingly that is, these results may indicate a crucial temporal constraint for the representation of distance, isolated in the visuomotor system. These findings are consistent with the general distinction between vision for perception (VI) and vision for action (MI) as advanced by Milner and Goodale (1995).

In regard to the initial questions relevant to Experiment 2: Does VI and MI operate in similar, separate, or parallel streams? The response-delay effects indicate that MI and VI appear to be mediated by separate cognitive processes. MI would appear to be associated with the dorsal (visuomotor) stream, whereas VI seems to be connected to the ventral stream.

Is MI affected by response-delay, similar to how actual movement is affected by pre- movement-delay? MI seems to be affected by response-delay just like actual movement is affected by pre-movement delay. In fact, Bradshaw et al. (2004) demonstrated that reaches following pre-movement delay had longer movement durations, lower peak velocities, larger peak apertures and longer time spent in the final

slow phase of the movement. They concluded that the introduction of a temporal-delay affected the accuracy of the pointing movement.

Does r accuracy of perceived reach under VI remain unaffected by response-delay? Our data, as well as data from studies using perceptual-matching tasks (e.g. Bradshaw & Watt, 2002), revealed that temporal-delay does not affect the accuracy of the response.

In summary, it appears that VI and MI operate in separate streams. VI seems to be linked to the perceptual or ventral stream and therefore does not account for the kinematic representation of movement resulting in less accurate responses in perceived reach. On the other hand, MI is likely connected to the visuomotor / dorsal stream and therefore follows the kinematic rules of actual movements resulting in more accurate responses. Delay seems to only affect MI which may reflect a major temporal constraint on the representation of movement through the visuomotor stream. In general, these data support the theoretical model of Milner & Goodale (1995), in which the dorsal stream computes distance information in real time.

CHAPTER IV

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The primary purpose of this research was to explore fundamental questions about the relationship between motor (MI) and visual imagery (VI) within the context of estimating reach. That is, does VI and MI operate in similar, separate, or parallel streams? Stated differently, are perceptual and biomechanic representations processed in similar, separate, or parallel VI and MI processes? And if the two streams are in fact separate, how are visual representations transformed into MI? How accurate are we at perceiving reachability under a VI paradigm, assuming that VI does not account for biomechanical constraints? Is MI affected by response-delay, similar to how actual movement is affected by pre- movement-delay? Does reaching accuracy under VI remain unaffected by response-delay? To address these questions two experiments were conducted.

Using an interference paradigm, the aim of Experiment 1 was to examine and compare VI and MI tasks under matched environmental conditions to explore the distinction and cooperation of the visual and motor systems in representing actions. Given the assumption that the ventral stream is "metrically" challenged and the dorsal stream is a "metrically" accurate stream (Goodale, 1998), we predicted that participants would make more errors in VI compared to MI. Also, for the interference tasks, we predicted that significant increases in the number of errors would be interpreted as evidence that the two tasks are in competition for space on the same processing pathway.

Significant increases in the number of errors or estimation bias was expected when the modalities for the imagined task and the interference task were matched.

Results indicated that the general response profiles for the baseline condition (MI vs. VI) were significantly different with more error in VI. These results agree with Solodkin et al. (2004) suggesting that different networks are used for VI and MI. The researchers used fMRI to distinguish between VI, MI and executed movements. Although our objectives did not include a measure of movement time, results to some extent support the conclusions of Stevens (2005) suggesting that Fitt's Law holds for MI, but not for VI. That is, MI and VI seem to recruit distinct visual pathways; the baseline differences found between MI and VI also support the views of Goodale and Milner (1992) stating that visual processing used in programming and controlling an action are different from processes needed for the perception and recognition of objects. This baseline difference provided a theoretical basis to carry out the interference effects.

In reference to MI interference conditions, results of total error, distribution of error, and mean bias indicated a significant difference between MI and MI with motor interference (MM). In regard to VI conditions, results indicated a significant difference between VI and VI with visual interference (VV). The interference effects in Experiment 1 demonstrate the likelihood that separate cognitive processes are used for visuo-motor and visual representations.

In regard to our initial questions relevant to Experiment 1: *Does VI and MI operate in similar, separate, or parallel streams? Stated differently, are perceptual and biomechanic representations processed in similar, separate, or parallel VI and MI*

processes? The interference effects found appear to compliment the idea of separate cognitive processes mediating VI and MI. MI appears to be associated with the dorsal stream, whereas VI seems connected to the ventral stream. These findings are consistent with the theoretical model advanced by Milner & Goodale (1995), where a distinction is described between what has been called "vision for action" and "vision for perception"(p.131).

And if the two streams are in fact separate, how are visual representations transformed into MI? It appears that the mechanisms underlying VI are most likely used to perceive spatial cues such as object size and location. In contrast, MI would appear to be used to perceive absolute metric and biomechanical demands. According to Stevens (2005), "these two modalities of representation must operate in a simultaneous and succinct manner for meaningful mental accounts of movements within the environment to result" (p.18).

How accurate are we at perceiving reach under a VI paradigm, assuming that VI does not account for biomechanical constraints? As mentioned earlier, VI and MI seem to operate in separate streams. VI is probably connected to the ventral stream which does not account for kinematic representation of movement resulting in less accurate responses. In contrast, MI in our experiment appears to be associated with the dorsal stream which is restrained by the kinematic demands of the movement resulting in estimates of reach. In general, these findings are supported by Milner and Goodale's (1995) discussions suggesting that the dorsal stream computes absolute metrics and uses an egocentric frame of reference and is required for accurate actions. They also contend

that the ventral pathway uses an allocentric frame of reference and computes relational metrics, giving detailed representation of the environment.

Experiment 2 examined the role of visual representation and response-delay in judgments of reachable distances. According to Goodale, et al. (2004), visuomotor processes responsible for action control (and used in MI) do not retain memory information about the target. Therefore, MI after a delay most likely depends on information derived from early perceptual processing in the ventral stream. Given the assumption that imagined and real movements follow similar neurocognitive pathways, we predicted that introducing a response-delay would decrease accuracy in the MI condition as shown in studies of actual movement execution (e.g., Bradshaw et al., 2004). Given the assumption that the system involved in visuomotor control has only limited memory, we predicted that performance of reachability after a delay may rely on the ventral (perceptual stream) stream and combined MI-delay conditions profiles would become comparable to all VI-delay conditions. The overall results of this experiment showed clearly that introducing a temporal-delay affected the ability to perceive reachability in MI conditions when a 4 s-delay was introduced, but not in VI conditions. From these results a key observation directed our attention; the fact that MI was affected by delay, but VI remained relatively unaffected and invariable when a delay was introduced. In regard to this result, although perception of reachability for both MI and VI was restricted by the same spatial parameters of the perceived environment, the translation of this information within each modality seems to be different. An alternative explanation to these results is that participants may still be using the dorsal motor stream

but since that stream does not operate in real time, the outcome resulted in an increase of error when a delay was introduced.

In regard to the initial questions relevant to Experiment 2*: Does VI and MI operate in similar, separate, or parallel streams?* The response-delay effects show that MI and VI appear to be mediated by separate cognitive processes. MI seems to be associated with the dorsal (visuomotor) stream, whereas VI appears to be connected to the ventral stream. *Is MI affected by response-delay, similar to how actual movement is affected by pre- movement-delay?* MI seems to be affected by response-delay just like actual movement is affected by pre-movement delay. Similar findings were reported by Bradshaw and Watt (2004) demonstrating that reaches following pre-movement delay had longer movement durations, lower peak velocities, larger peak apertures and longer time spent in the final slow phase of the movement. They concluded that the introduction of a temporal-delay affected the accuracy of the pointing movement. *Does perceived reaching accuracy under VI remain unaffected by response-delay?* Our data, as well as data from perceptual-matching studies (e.g. Bradshaw & Watt, 2002), indicate that temporal-delay does not affect the accuracy of the response.

These data (Experiment 1 and 2), taken together address the greater question of whether VI and MI operate in similar, separate, or parallel streams. In both experiments, there were significant differences between baseline motor and visual imagery. The baseline condition results (MI vs. VI) indicate that overall, participants in MI are more accurate then in VI. These differences are consistent with the views of Goodale et al. (2005) stating that the visual processing used in programming and controlling an action

are different from processes needed for the perception and recognition of objects. These findings also support the works of Solodkin et al. (2004), suggesting the use of different networks for MI and VI. In fact, the researchers concluded that MI follows processes comparable to executed movements (e.g. Fitt's law) whereas VI does not. Also, as mentioned earlier, our setup had no movement time component, these results to some extent support the conclusions of Stevens (2005) suggesting that Fitt's Law holds for MI, but not for VI.

The results of both experiments appear to compliment the "two-visual systems" model described by Milner & Goodale (1995) and recently updated by Goodale et al. (2005). This model advocates that visual processing used in programming and controlling an action is different from visual processing needed for the perception and recognition of objects. The researchers suggested that visually guided movements are mediated by visuomotor systems in the dorsal stream. They also argue that the perception and recognition of objects is mediated by ventral-stream projections, which also arise in the primary visual cortex, but project into the temporal lobe. According to this account, the perceptual processes in the ventral stream use allocentric frames of reference that give meaning to the environment such as object recognition and object location. In contrast, the dorsal stream uses egocentric frames of references and calculates absolute metrics necessary for rigorous and efficient movements.

Consistent with the ideas of Goodale et al. (2005), our results indicate that MI is more accurate then VI. The dissociation found between MI and VI was present despite the fact that the experimental paradigm remained identical. Both experiments were run

in darkness (except for the targets projected on the table) to exclude other visual cues that might be present within the environment; in other words, egocentric direction and distance were encouraged. The ventral stream is thought to work better within an allocentric frame of reference which might have also contributed to baseline differences in total error between MI and VI.

In regard to Experiment 1, with the interference conditions, we found that MI was only affected when a motor interference was introduced and VI was only affected when visual interference was introduced. These findings would seem to indicate separate processing channels where VI most likely represents scene based characteristics, while MI is used to represent biomechanical parameters. In regard to Experiment 2, MI-delay accuracy decreased when a 4 s was introduced, whereas VI-delay remained invariable. These results are in agreement with the "two-visual system" model advocating that the perceptual system represents objects and stores them in memory for later actions, whereas the dorsal stream operates in 'real-time' using egocentric information and absolute metrics, required for accurate movements. Also, another key result that also supports the "two visual system" model is that MI-delay profile looked very similar to VI-delay profile. In other words, the control of reaching in MI after a delay depended on information derived from mechanisms in the perceptual (ventral) stream.

A major theoretical question remains to be addressed and answered: are the ventral and dorsal streams independent? Or linked? Several recent findings support the general idea that perception and action are mediated by independent visual systems that compute information present on the retina differently. Neurophysiological evidence from

visual agnosia (Goodale, Jackobson, & Keillor, 1994) and optic ataxia (e.g., Revol, Rossetti, Vighetto, Rode, Boisson, & Pisella, 2003; Rossetti, Pisella, & Vighetto, 2003) reasearch provide support for two separate pathways; one for object-oriented action operating in real time and depending on visuomotor networks in the dorsal stream, and the second operates offline and depends on the perceptual mechanisms in the ventral stream. Using a variety of tasks, researchers have demonstrated critical differences between perception of a stimuli and control of action on that stimuli; underscoring the notion that perception and action engage distinct visual pathways (Burr, Morrone, & Ross, 2001; Brown, Moore, & Rosenbaum, 2002; Dubrowski & Carnahan, 2002; Churchland, Gardner, Chou, ,Priebe, &Lisberger,2003; Kerzel & Gegenfurtner, 2003; Whitney, Westwood, & Goodale, 2003). Also, several experiments have shown that actions, such as grasping that are initiated *after* a delay (when the objects is no longer visible) are different from actions initiated while the object is visible (Hu & Goodale, 2000). Although our study does not fully substantiate the exact use of visual information, our data is consistent with the two visual system hypothesis. These findings suggest that the control of actions after a delay may depend heavily on processing in the ventral stream (Goodale et al.2005). As a reminder, our results from Experiment 2 support these findings in that all MI-delay conditions became very similar to overall VI-delay conditions.

Although the two streams are distinct in nature, the updated account of the two-visual system model advocates that the ventral and dorsal streams, just like perception to action, are tightly linked (Guillery, 2005, Stevens, 2005). For example, research has

demonstrated that allocentric (ventral) and egocentric (dorsal) frames of reference interact to influence the trajectory and accuracy of a movement (Bradshaw et al., 2004; Krigolson & Heath, 2004; Stevens, 2005). Interestingly, the idea of the interaction of processes, rather than separate and distinct, is much more pronounced in recent updates of the two-visual system model as described by Goodale et al. (2005), and interpreted (by us) from the works of Bradshaw et al. (2004) and Stevens (2005).These findings suggest that the ventral and dorsal streams interact *(couple)* to enhance optimal behavior. Research shows that many actions depend on complex stimuli that can only be interpreted via the ventral stream (e.g. Goodale et al, 2005). The link between the visuomotor and perceptual stream support findings from several neurophysiological experiments reporting neurons in the posterior parietal cortex that are sensitive to stimulus features such as color and shape (e.g. Toth & Assad, 2002) in paradigms where the stimuli are randomly mapped to object-directed actions; i.e. neurons in the dorsal stream are selective to particular visual stimuli that are related to the required response rather than to the perceptual processing.

Although the present experiments addressed several prominent questions, our explanations were limited to behavioral work. First, despite the fact that we found a difference between MI and VI, there remains a slim possibility that participants in every trial did not kinesthetically imagine the reaching movement. Complementing this possibility, the nature of the task could have been a limitation; to our knowledge this is the first study to examine VI and MI in the context of perceived reach. Visual imaging a reaching action is more challenging then for example, looking at a disc moving (Stevens,

2005) because it is hard to disengage the self from the action. This study was also limited in the context of perceived reach rather then actual and kinematic parameters. Another limitation to this study is that our explanations for underestimation values were only based on speculations about confidence. Finally, our paradigm, due to its behavioral nature, could not depict the areas of the brain involved in MI and VI.

In regard to extension of this work, future studies should investigate the extent to which visual structures around a target might affect perceived reach accuracy. It has been shown that introducing a visual structure (physical or perceived) around a target enhances the accuracy of memory-guided actions (e.g. Lemay, Bertram, & Stelmach, 2004; Krigolson & Heath, 2004). These results support the notion that memory-guided movements, as opposed to visually guided movements, rely on perceptual networks in the ventral stream that use a scene-based frame of reference. Such a study would reexamine the present conclusions that overlapping networks for visual pathways are critical for accurate reachability estimates.

In summary, the present set of experiments demonstrates that motor and visual imagery are processed within overlapping visual channels. The interference effects used in Experiment 1 demonstrated that motor tasks interfered with the ability to MI**,** whereas visual tasks interfere with the ability to VI. Experiment 2 demonstrated that the effect of a response- delay influenced accuracy of the MI (visuomotor) task, but not the VI (perceptual) task. Interestingly, these results may indicate a crucial temporal constraint for the representation of distance, isolated in the visuomotor system. Taken together, these findings are consistent with the general distinction between vision for perception

(VI) and vision for action (MI) as advanced by Milner & Goodale (1995) and updated by Goodale et al. (2005). VI seems to delineate relevant spatial parameters within the environment and then transfer the information to MI, which in turn computes this information in terms of biomechanical possibilities for a certain movement Perhaps the original statement from Musseler, Steininger and Wuhr (2001) - *where perceptual processes end, cognitive processes start, and execution of motor actions begin, is key and yet to be define* - needs to be revised in view of the updated version of the two-visual systems; perhaps a more relevant question that needs to be solved is "*how the two visual streams work together in the control of our behavior"* (Goodale et al., 2005).

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Research interests

Perceptual and motor processes involved in limb selection and reaching (developmental perspective)

Publications

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